504

replaces California Institute of Technology Social Science Working Paper #504

Practical Implications of Game Theoretic Models of R&D

By JENNIFER F. REINGANUM*

The purpose of this paper is to survey recent game theoretic models of research and development, and to ask whether they yield practical implications or testable hypotheses. The papers I will be discussing have been written or published within the past five years; they have a good deal in common, relying upon similar assumptions and building upon each other. Because of this, the literature surveyed here may seem narrow, and some relevant work has probably been inadvertently omitted. I apologize for these omissions. For want of space, I will not discuss the normative conclusions of this literature.[1]

I. Why Game Theory?

As students of industrial organization, we cannot ignore interactions among the agents we study. Positive industrial organization is the study of business policy and strategy. Modern noncooperative game theory is a language of strategy and equilibrium; that is, it provides an equilibrium framework in which to examine individuals' strategic behavior. Recent advances, for instance the theory of supergames (James Friedman, 1971) and the notions of perfect equilibrium (Reinhard Selten, 1975) and sequential rationality (David Kreps and Robert Wilson, 1982), have made game theory an even more powerful tool for examining controversial issues in industrial organization. All models must postulate the behavior of some agents in the model; a game theoretic model must, in addition, impose certain consistency checks, or equilibrium conditions, upon this postulated behavior. Within the confines of the game theoretic paradigm, there are still many alternative modeling choices regarding, for example, informational assumptions and timing conventions. Thus the paradigm is capable of generating a wide range of equilibrium behavior. As with any theory, the ultimate appeal for validation or vitiation is to empirical testing. I will isolate and discuss several implications, most of them controversial, from the recent literature. This seems to be a useful first step toward the goal of empirical testing.[2]

II. The Implications of Recent Models

Because most of the papers discussed below analyze and extend a single basic model, I provide a brief description of this model. Partha Dasgupta and Joseph Stiglitz (1980) and Glenn Loury (1979) employ a model of stochastic invention in which the probability of success by firm i by a given time, t, is an exponential function. That is, if t_i represents firm i's (random) success date, then $Pr(t_i \leq t) = 1 - e^{-h_i t}$, where h_i is the "hazard rate," or conditional probability density of success, given no success to date. The choice variable

*Division of Humanities and Social Science, California Institute of Technology, Pasadena, CA 91125. I thank Therese Flaherty, Nancy Gallini, Avinash Dixit, and Alan Schwartz for helpful comments and suggestions. The financial support of the National Science Foundation is gratefully acknowledged.

[1] For a more complete survey of the previous empirical and theoretical literature on this subject, see Morton Kamien and Nancy Schwartz (1982). For a detailed account of previous empirical work and a discussion of appropriate measurement and methodology, see David Grether (1974).

[2] Although previous empirical work is suggestive, most of it has not been carried out with a specific behavioral model of the firm in mind. Moreover, it has tested hypotheses which were couched in much more aggregated terms than those to be discussed below.

for each firm i is a lump sum expenditure x_i at time $t=0$, which implies a hazard rate of $h_i = h(x_i)$. With this specification, the expected time till success for firm i is the reciprocal of the hazard rate; $E(t_i) = 1/h(x_i)$. The innovation "production function" $h(x)$ is allowed to have initial increasing returns to scale, but eventually decreasing returns set in. Patent protection is assumed perfect, firms are identical, and no further innovation is anticipated. This problem is modeled as a simultaneous-move game, and the equilibrium concept is Nash equilibrium in investment strategies. Tom Lee and Louis Wilde (1980) modified this formulation by assuming that the investment is a *flow* cost, rather than a lump sum payment at the initial date. That is, firm i pays at the rate x_i, but only until someone succeeds. They maintain all of the remaining assumptions of the model. The first three implications turn on this difference in the specification of costs.

1. The amount invested by an individual firm decreases with the number of firms engaging in *R&D*; however, aggregate industry investment increases with the number of firms.

1′. The *rate* of investment by an individual firm increases with the number of firms engaging in *R&D*; a fortiori, the aggregate industry investment rate increases with the number of firms.

Using the Dasgupta-Stiglitz and Loury fixed cost model, one can conclude that the equilibrium amount invested by any one firm decreases with the number of firms engaged in research and development. Despite this, an increase in the number of firms engaged in *R&D* results in an increase in aggregate investment. From the Lee-Wilde flow cost model, one can deduce that the equilibrium rate of expenditure per firm increases with an increase in the number of firms; a fortiori, aggregate investment increases with the number of firms. The intuition behind these conclusions is simple. In the Dasgupta-Stiglitz and Loury model, an increase in the number of firms reduces the expected benefit to investment (a particular firm is less likely to win), leaving expected costs unchanged. The firm responds by reducing investment. In the Lee-Wilde model, both expected benefits and expected costs are reduced by the addition of another firm (since the flow investment will be made for a stochastically shorter period of time), and the net effect is to enhance incentives to invest. Implications 1 and 1′ are not inherently contradictory; it is quite possible that although the flow rate of investment increases, expected discounted flow costs decrease with an increase in the number of firms. What *are* contradictory are these models' respective implications regarding the effect of an increase in the number of firms upon the expected time until success for an individual firm. Since in both cases, $E(t_i) = 1/h(x_i)$, we see that the fixed cost model implies that $E(t_i)$ increases with the number of firms, while the flow cost model implies that $E(t_i)$ decreases with the number of firms.

When one relaxes the assumption of perfect patent protection, it is easy to construct examples in which an increase in the number of firms decreases the individual rate of investment in a flow cost model; this is because if imitation is a sufficiently attractive alternative, the firm is less concerned about being first (see my 1982 paper). In fact, when imitation is sufficiently swift and complete, there may be an inverse relationship between *aggregate* investment and the number of firms in the industry (Carl Futia, 1980). An alternative form of nonappropriability occurs when rival firms experience significant positive spillovers from each others' research and development expenditures. If these spillovers are sufficiently large, then aggregate investment is inversely related to the number of firms in the industry (Michael Spence, 1982). Thus both the degree of appropriability and the number of firms have direct effects on investment; in addition, there are interaction effects between the degree of appropriability and the number of firms. Since the number of firms engaging in *R&D* is also endogenous, any test of these hypotheses requires a simultaneous equations approach.

2. In a Nash equilibrium with unrestricted entry, there will be excess capacity in the *R&D* technology.

2′. In a Nash equilibrium with unrestricted entry, there will be no excess capacity in the *R&D* technology.

In the lump sum expenditure model of Loury and Dasgupta-Stiglitz, it can be shown that with unrestricted entry, in equilibrium firms will operate their *R&D* projects in a region of increasing returns to scale. In the flow cost model of Lee-Wilde, this result is reversed; firms will always operate in the decreasing returns portion of the innovation production function.

3. At equilibrium, an increase in aggregate rival investment results in a decrease in investment by a single firm.

3′. At equilibrium, an increase in the aggregate rival investment rate results in an increase in the rate of investment by a single firm.

In the fixed cost models, the profit-maximizing investment is smaller the greater is aggregate rival investment, while in the flow cost models, the profit-maximizing rate of investment is greater the greater is the aggregate rival investment rate. Alternatively put, in the fixed cost models, best response functions are decreasing at equilibrium, while in the flow cost models, they are increasing.

These models all focused upon symmetric equilibria in which no previous innovation was assumed and no future innovation is anticipated. Any stochastic theory of industry evolution will give rise to asymmetric initial conditions; moreover, M. Therese Flaherty (1980) has demonstrated the manner in which industry members who are initially identical may end up following divergent paths even when industry evolution is completely deterministic. In view of these theoretical considerations as well as the obvious empirical fact of asymmetry, it is important to develop asymmetric models of innovation if we wish to apply them to real industries. The models discussed below add such an asymmetry, either through an inherited asymmetric market structure, or through the assumption of a leader/follower, rather than simultaneous-move, framework. The next few implications deal with the impact of current monopoly power and anticipated future innovation upon incentives to invest in *R&D* when firms invest simultaneously.

4. There is an inverse relationship between the magnitude of an innovation and the likelihood that it is invented by a current industry leader.

5. Investment in *R&D* is lower for a large incumbent firm and challengers alike the greater is the flow of current revenue to the incumbent firm.

6. The rate of individual firm investment on a particular innovation declines with the number of anticipated subsequent innovations.

These results follow from the model of a sequence of innovations developed in my forthcoming article. An innovation is termed drastic if the innovator captures a sufficiently large share of the post-innovation market; that is, if the innovation substantially replaces whatever product or process was previously used. When firms anticipate a sequence of drastic innovations, the current industry leader, or incumbent, invests less than each challenger and will thus succeed itself as incumbent (on average) less than $1/n$ percent of the time, where n is the number of firms. The intuition behind this result is straightforward. When invention is uncertain, a firm making higher profits today gains relatively less from invention than a firm with lower current profits; consequently, an industry leader invests less than a challenger or potential entrant. A simple extension of this model indicates that for innovations which are minor (i.e., for which the innovator captures a sufficiently small fraction of the market), the incumbent will invest more than a challenger. Thus we would expect an inverse relationship between the magnitude of the innovation and the likelihood that it is developed by a current industry leader. Moreover, this implication is robust to changes in the specification of costs; that is, this result is insensitive to the fixed versus flow cost assumption. Using a single innovation, fixed cost model with one incumbent monopolist and one challenger, Richard Freeman (1982) found that for large innovations a single challenger will invest more on *R&D* than an incumbent monopolist; Thomas von Ungern-Sternberg (1980) found that for small innovations an incumbent monopolist will invest more than a challenger, and that the probability that the monopolist will succeed first is decreasing with the magnitude of the innovation.

The second implication above is a pure equilibrium effect. An increase in flow revenues to the incumbent has no direct effect upon the challenger's payoff; however, it does induce the incumbent to invest at a lower rate. Because my model (forthcoming) employs a flow cost specification, best response functions are increasing; consequently, the equilibrium response of challengers is to reduce their investment as well.

Finally, implication 6 is a consequence of two effects; a sequence of anticipated future innovations reduces the value of being the incumbent (because no firm can expect a long tenure as incumbent when many innovations remain), and increases the value of being a challenger (because one has many remaining opportunities to succeed). These two effects combine to reduce current investment in *R&D*.

The following implications discuss the impact of changing the timing of the game; suppose that there is a leader/follower structure (in which the incumbent monopolist moves first) rather than a simultaneous-move structure.

7. If the innovation production process is nonstochastic, then a firm which currently dominates an industry will persist as a monopolist, because it will preemptively patent innovations before potential entrants.

8. The above argument holds only if the industry is one in which the threat of antitrust intervention precludes *ex post* negotiation and exclusive licensing. If *ex post* licensing is permitted, the most efficient firm would patent the innovation, but this need not be the incumbent.

The model which generates the first of these implications appears in Dasgupta-Stiglitz (1980), and is more fully developed in Richard Gilbert and David Newbery (1982). Gilbert-Newbery describe a bidding model of *R&D* in which invention is deterministic; thus the question of who invents is essentially one of who has the most to gain from doing so. An entrant will be willing to bid post-innovation duopoly profits for the innovation. By permitting entry, the incumbent and the entrant receive post-innovation duopoly profits; by preemptively patenting the innovation, the incumbent receives post-innovation monopoly profits. Since the present value of monopoly profits exceeds the sum of duopoly profits, the monopolist will bid more for the innovation (i.e., patent it before the entrant). The qualification is voiced by Stephen Salant (1984), who argued that if an entrant anticipates the possibility of innovating and subsequently selling out to the current incumbent, then it will not evaluate the gains from inventing as merely its share of duopoly profits, but will include the expected gains from licensing its patent to the incumbent. In this case, the most efficient firm —not necessarily the incumbent—would patent the innovation.

9. Licensing encourages research when production costs are relatively similar, and discourages research when production costs are relatively disparate.

In a two-firm model of research and development with licensing, Nancy Gallini and Ralph Winter (1983) discuss two incentives to license. The first of these, termed the *ex post* incentive, is the one identified by Salant —the incentive to reduce production inefficiencies and monopolize the output market. There is also an *ex ante* incentive to license (originally identified by Gallini, 1983), which reflects the gain from eliminating wasteful research expenditures as well as the threat of a potentially low-cost competitor. By licensing its technology to a potential challenger at a sufficiently low royalty rate, an incumbent firm can make *R&D* a less attractive prospect to the challenger; this simultaneously reduces expenditures on *R&D*, and removes the threat that the challenger may discover a very low-cost technology. Thus a large *ex post* incentive makes research attractive, while a large *ex ante* incentive reduces the return to research. When production costs are sufficiently similar, *ex ante* incentives are too weak to dominate the gains from *R&D* generated by *ex post* incentives, and investment is encouraged. When production costs are sufficiently dissimilar, *ex ante* incentives dominate, and investment is discouraged. Empirical testing again would require a simultaneous equations approach in which investment in research and development and some measure of licensing behavior are to be explained.

10. Over the course of developing an innovation, the configuration of firms engaging in *R&D* will become more concentrated

as some firms fall sufficiently far behind and, consequently, drop out.

Equilibrium behavior in the models of Drew Fudenberg et al. (1983) and Christopher Harris and John Vickers (1983) is characterized by this pattern. There is an initial burst of investment in which several firms participate; however, when rival firms fall sufficiently far behind the leader, they prefer to drop out of the competition. Consequently, the leader completes the innovation at its preferred, more leisurely, pace. Although extremely stylized, these models incorporate learning and experience in a way not found in previous work.

III. Conclusions

Although individual models have unambiguous implications, the array of existing models still generates considerable controversy. This heightens the interest in and need for empirical tests of these theories. Unfortunately, these implications are generated by highly simplified models, which may make empirical testing more difficult. For instance, some very real aspects of industrial competition are left out, including the possibility of incumbent advantages (for example, better access to capital markets, internal financing, economies of scope) and disadvantages (for example, bureaucratic red tape, weak employee incentives due to a tenuous connection between performance and reward). Also left out are the possible effects of conglomerate diversification; all of these models compare expenditures in a single research area, rather than in the sort of diversified portfolio of projects which might be common among large firms.

Although some sources of data which are suitable for testing these hypotheses do exist, much of the existing data is too aggregated. In addition, many of these hypotheses rely on data which may be difficult to obtain, such as information about the research programs of unsuccessful firms. In order to move in the direction of empirical testing, we must both extend these models in more realistic directions to accomodate existing data, and attempt to gather the specific data required to test directly such models of firm behavior.

REFERENCES

Dasgupta, Partha, "The Theory of Technological Competition," Discussion Paper, International Centre for Economics and Related Disciplines, London School of Economics, 1982.

______ **and Stiglitz, Joseph** "Uncertainty, Industrial Structure and the Speed of *R&D*," *Bell Journal*, Spring 1980, *11*, 1–28.

Flaherty, M. Therese, "Industry Structure and Cost-Reducing Investment," *Econometrica*, July 1980, *48*, 1187–209.

Freeman, Richard, "A Model of International Competition in Research and Development," manuscript, Federal Reserve Board, December 1982.

Friedman, James W., "A Noncooperative Equilibrium for Supergames," *Review of Economic Studies*, January 1971, *28*, 1–12.

Fudenberg, Drew et al., "Preemption, Leapfrogging and Competition in Patent Races," *European Economic Review*, No. 1, 1983, *22*, 3–31.

Futia, Carl A., "Schumpeterian Competition," *Quarterly Journal of Economics*, June 1980, *95*, 675–95.

Gallini, Nancy T., "Strategic Deterrence by Market Sharing: Licensing in Research and Development Markets," manuscript, University of Toronto, 1983.

______ **and Winter, Ralph A.,** "Licensing in the Theory of Innovation," manuscript, University of Toronto, 1983.

Gilbert, Richard J. and Newbery, David M. G., "Preemptive Patenting and the Persistence of Monopoly," *American Economic Review*, June 1982, *72*, 514–26.

Grether, David M., "Market Structure and *R&D*," Caltech Social Science Working Paper No. 58, 1974.

Harris, Christopher and Vickers, John, "Perfect Equilibrium in a Model of a Race," manuscript, Oxford University, February 1983.

Kamien, Morton I., and Schwartz, Nancy L., *Market Structure and Innovation*, Cambridge: Cambridge University Press, 1982.

Kreps, David M. and Wilson, Robert, "Sequential Equilibrium," *Econometrica*, July 1982, *50*, 863–94.

Lee, Tom and Wilde, Louis L., "Market Structure and Innovation: A Reformulation," *Quarterly Journal of Economics*, March 1980, *94*, 429–436.

Loury, Glenn C., "Market Structure and Innovation," *Quarterly Journal of Economics*, August 1979, *93*, 395–410.

Reinganum, Jennifer F., "A Dynamic Game of *R&D*: Patent Protection and Competitive Behavior," *Econometrica*, May 1982, *50*, 671–88.

______, "Innovation and Industry Evolution," *Quarterly Journal of Economics*, forthcoming.

Salant, Stephen W., "Preemptive Patenting and the Persistence of Monopoly: Comment," *American Economic Review*, March 1984, *74*, 247–50.

Scherer, F. M., *Industrial Market Structure and Economic Performance*, 2d. ed., Chicago: Rand McNally, 1980.

Selten, Reinhard, "Reexamination of the Perfectness Concept for Equilibrium Points in Extensive Games," *International Journal of Game Theory*, No. 1, 1975, *4*, 25–55.

Spence, Michael, "Cost Reduction, Competition and Industry Performance," Harvard Institute of Economic Research, Discussion Paper, 1982.

von Ungern-Sternberg, Thomas, "Current Profits and Investment Behavior," *Bell Journal of Economics*, Autumn 1980, *11*, 745–48.